Estimation of Temporally Evolving Typhoon Winds and Waves from Synthetic Aperture Radar

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LONG-TERM GOALS

The long term goal is to develop a methodology for using synthetic aperture radar (SAR) data to improve characterization of the winds and waves generated by typhoons in the western Pacific Ocean.

OBJECTIVE

The objective is to develop a variational assimilation algorithm based on the SWAN model to estimate the near-surface typhoon wind field from SAR data.

APPROACH

Third-generation wave spectrum models such as SWAN can be used to predict wind-generated waves. Combining SWAN and a model relating the SAR-image spectrum to the computed wave spectrum, one can predict the SAR-image spectrum which results from a known wind field. Using variational data assimilation, this relationship can be inverted to estimate the wind field from SAR data. This approach uses adjoint versions of the SWAN and SAR models to calculate the gradient of the error of the predicted SAR data with respect to the input wind field. This gradient is used to iteratively adjust the wind field to produce a wave field from SWAN that yields a best-fit to the SAR data.

WORK COMPLETED

An algorithm for estimation of temporally evolving winds has been developed. It is based on an existing assimilation algorithm for the SWAN wave model and SAR data, developed to estimate the ocean-wave field for a near-shore region for stationary conditions using SAR data (Walker 2006). The algorithm is variational in nature and is based on the SWAN 40.51 ocean-wave-spectrum model (Ris *et al.* 1999, Booij *et al.* 1999) coupled to the nonlinear SAR-spectrum model of Hasselmann and Hasselmann (1991). In its original form, the algorithm was used to estimate the boundary conditions for SWAN that result in a wave-spectrum prediction which best fits the SAR data. An expression for the gradient of the cost function (the error in the estimates of the data) with respect to the input wind field in terms of the forward and adjoint solution was first developed, and then the algorithm was extended to to include wind estimation for non-stationary conditions. This required: (1) extension of the SWAN code to efficiently save the entire five-dimensional forward solution; (2) extension of the adjoint SWAN solver to work for non-stationary conditions, to read in the forward solution time

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history, and to ingest observation data at arbitrary locations and times; and (3) development of ancillary codes to calculate the gradient from the forward and adjoint SWAN solutions, adjust the wind field, and control the iteration process. These have been completed. In addition, the wind-wave generation modeling in SWAN (Wu 1982) was updated to include high-wind-speed effects on the drag coefficient correlation consistent with the results of Donelan *et al.* (2004).

RESULTS

Initial application of the SWAN/SAR wind-estimation algorithm was for the Atlantic storm Hurricane Helene over the period from 14–24 September 2006. During this period, the hurricane reached maximum sustained winds of 55 m/s (105 kts) on 18 September. The initial guess for the winds over this period were Navy Operational Global Atmospheric Prediction System (NOGAPS) wind fields at three-hour intervals, comprised of analysis fields at six-hour intervals interleaved with forecast fields. Figure 1 shows the Atlantic basin with the storm track for Helene for the period in question. Also shown are the locations of nearly 800 valid European Space Agency Envisat Advanced SAR (ASAR) Wave Mode wave spectrum estimates during this period and the locations for two Radarsat-1 SCANSAR images for 19 and 20 September. The algorithm development work done to-date made use of the ASAR Wave Mode data and those results are presented below. The algorithm is presently being adapted for the Radarsat-1 data.

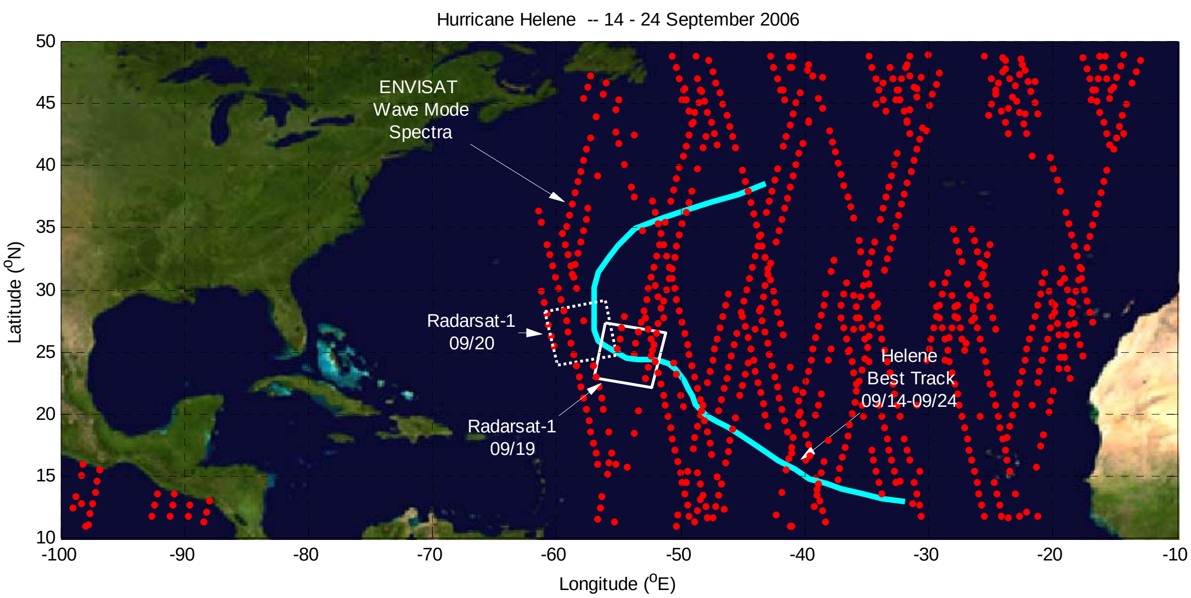

Figure 1. Storm track for Hurricane Helene from 14-24 September 2006. Also shown are the locations of available Radarsat-1 imagery of Helene for 19 and 20 September and symbols showing the location of all valid Envisat Wave Mode spectra over the time period.

Figure 2 shows the iteration history for the cost function. For Helene, we used 779 Wave Mode spectrum observations as the assimilation data and the NOGAPS wind fields from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) as the initial guess for the wind field. The cost function is a measure of the error variance for the predicted wave spectra plus a contribution proportional to the mean-square deviation of the estimated wind field from the initial guess. This latter contribution is included to ensure the uniqueness of the best-fit solution and is weighted to comprise no

more than a few percent of the cost function. In Figure 2, the cost function is seen to decrease and begin to flatten out by iteration six and the algorithm terminates after eight iterations. Since each iteration requires between 5 and 10 forward runs of the SWAN code, this represents 67 SWAN forward-model runs as well as eight SWAN adjoint-model runs, one for each iteration. In Figure 2, the cost function can be seen to decrease by about fifteen percent; this is being investigated but may be due to differences in the details of the spectral shape produced by SWAN in response to wind forcing compared to the Wave Mode spectra for comparable significant wave height.

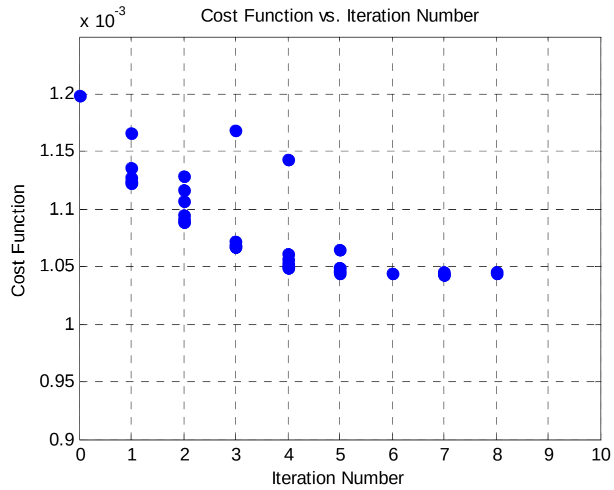

Figure 2. Cost function vs. iteration number for wind estimation from Envisat Wave Mode spectra for Hurricane Helene. The cost function is reduced by roughly 15 percent over 8 iterations. Multiple points plotted for each iteration show line minimization steps.

Figure 3 shows a comparison of the first-guess wind field and the converged estimate for 19 September at 03:00 GMT. At this time, the National Weather Service-National Hurricane Center (NWS-NHC) observed maximum winds for Helene were 49 m/s and the NOGAPS winds were at 24 m/s, while the SWAN/SAR estimate is 55 m/s. The location of the maximum in SWAN/SAR estimate is consistent with expectations: at this time the storm is moving due west and the maximum winds tend to be located to the right of the storm track. It is not clear whether the structure of the storm is consistent typical hurricane behavior and that will be investigated. Also shown in the images is the location of the storm center from the NWS-NHC best track, and a box which is +/-7.5 degrees in latitude and longitude relative to the storm center, used to automate the determination of the maximum sustained wind speed (we used the maximum wind speed inside the box centered on the storm location for each time). The location of the wave mode spectrum observations for this time are also plotted. Since these observations are some seven degrees to the east of the storm, they do not influence the estimate of the storm winds at this time, but they may at earlier times (since the data provides information waves generated elsewhere earlier in time that then propagate to the observation location); the changes in the estimated storm winds seen at this time result from data at later times.

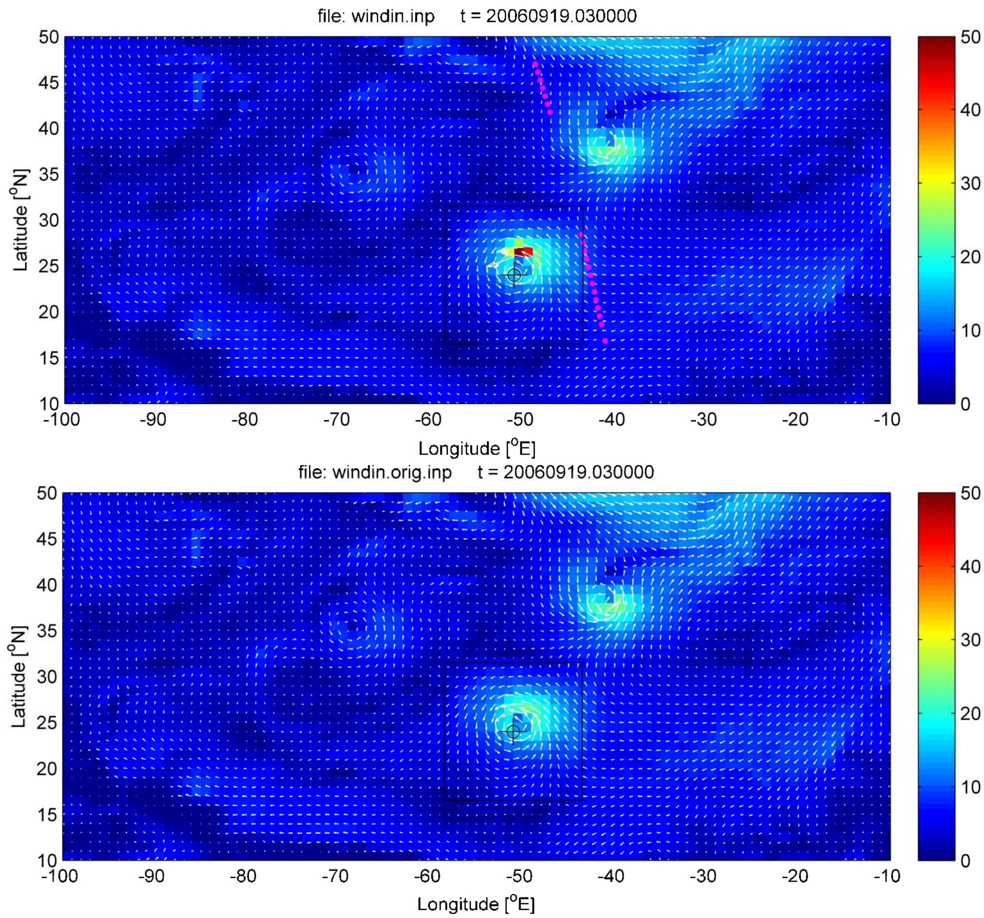

Figure 3. Comparison of the SWAN/SAR-estimated wind field (upper) and the NOGAPS initial guess (lower) showing an estimated increase in the hurricane winds. The maximum wind estimate is 55 m/s, up from the NOGAPS value of 24 m/s and close to the NWS-NHC value of 49 m/s. Also shown are the NWS-NHC best-track location of the storm center, the +/-7.5 degree box used to determine the maximum winds and, in the upper image, the locations of the Envisat Wave Mode spectra for this time.

Figure 4 shows a comparison of the maximum sustained winds over time for the SWAN/SAR estimates to the NWS-NHC best-track data and the FNMOC NOGAPS initial guess. The maximum winds for the SWAN/SAR results and the NOGAPS fields were taken as the maximum in a +/- 7.5 degree box centered on the NWS-NHC storm track (as shown in Figure 3, above). To get a sense of how the behavior relates to the times when Wave Mode data are acquired, Figure 4 also shows the times when the data were acquired within the 7.5 degree box centered on the storm. Comparison of the NWS-NHC speed data to the NOGAPS initial guess shows that the NOGAPS results substantially underestimate the wind speeds in the hurricane: the maximum NOGAPS speed is 29 m/s, while the NWS-NHC data indicate maximum winds of 54 m/s. For substantial stretches of time, the SWAN/SAR estimate does not deviate from the NOGAPS initial guess; looking at the data times plotted, it is seen that these correspond to time periods when no data was present near the storm. Roughly speaking, on days when data are present, the estimates deviate from the NOGAPS result in a way that makes the error smaller, in some cases matching the NWS-NHC data, and only in a few places exceeding it substantially (i.e. early on 9/16).

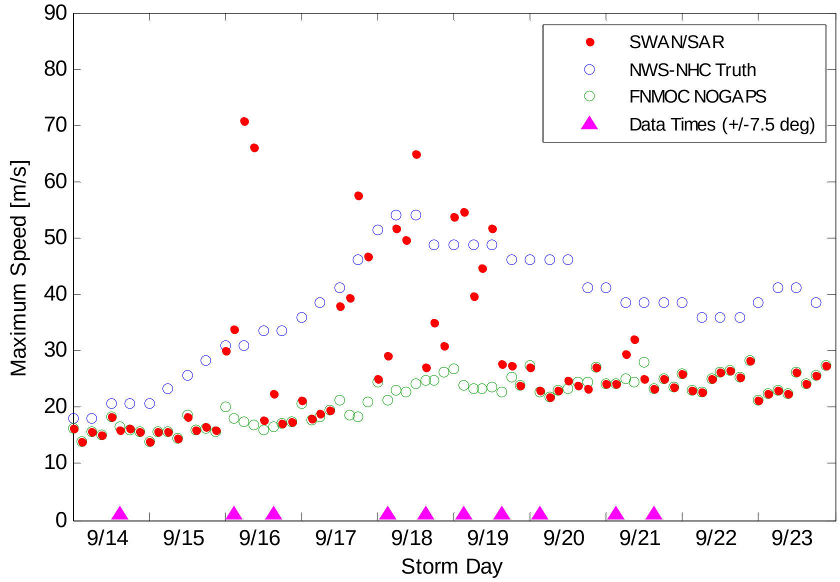

Figure 4. SWAN/SAR estimates of maximum sustained speed during Hurricane Helene along with times when data were acquired near the storm. Estimates based on assimilation of Envisat Wave Mode spectra with comparison to the FNMOC NOGAPS winds and the NWS-NHC best-track analysis. Significant improvement is shown for times when data were acquired near the storm. The NOGAPS winds were used as the first guess for the assimilation algorithm and maximum speed estimates for the algorithm and NOGAPS are the maximum in a 7.5 degree box centered on the storm location. This same box was used to determine when data were acquired close to the storm. Note that the estimated winds only deviate from the first-guess NOGAPS values on days when data were acquired and almost without exception the estimates are closer to the truth than the NOGAPS winds.

Figure 5 shows a direct comparison, plotting the NOGAPS and SWAN/SAR winds versus the NWS-NHC truth data. In Figure 5(a), the comparison is made for all times. Here, the bias toward low velocities in the NOGAPS winds is clearly seen; the mean error is -16.0 m/s and the root-mean-square (RMS) error is 17.7 m/s. For the SWAN/SAR estimates, the mean error is reduced by nearly half to -9.1 m/s and the RMS error is reduced to 14.8 m/s; both significant improvements. As noted above, there are substantial periods of time where the SWAN/SAR estimates are not affected by the data and so do not deviate from the NOGAPS initial guess. If we include only the SWAN/SAR results that deviate significantly (more than 10 percent) from the NOGAPS initial guess, we get the result shown in Figure 5(b). Here if we exclude the near 70 m/s estimate (which occurred on 9/19, mentioned above), the mean error drops to -3.3 m/s and the RMS error decreases to 2.8 m/s, a tremendous improvement. This shows the potential of the algorithm to improve wind estimates.

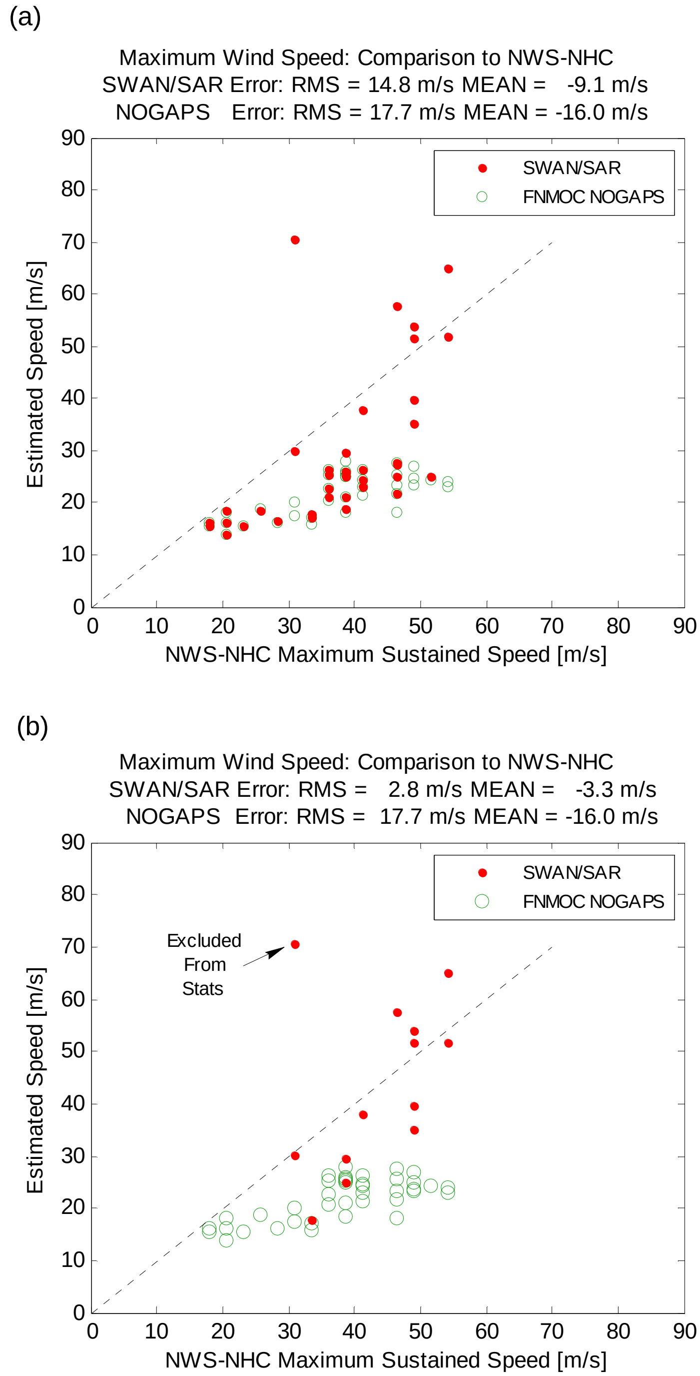

Figure 5. Comparison of estimated maximum wind speed to NWS-NHC truth data: (a) comparison of SWAN/SAR and NOGAPS estimates for all times; (b) comparison including SWAN/SAR wind speeds only from times influenced by the data. For all times the mean (RMS) error for the NOGAPS initial guess is -16 m/s (17.7 m/s) while that for the SWAN/SAR estimate is -9 m/s (14.8 m/s), a substantial improvement. If we only include data that deviated from the NOGAPS data, we get -3.3 m/s (2.8 m/s) for the mean (RMS) errors, showing the potential for the algorithm.

IMPACT/APPLICATIONS

If successful, the algorithm developed here will enable improved operational prediction of tropical cyclone evolution.

RELATED PROJECTS

This program is part of the ITOP Departmental Research Initiative

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